

AN OPERATIONAL TEST OF A NUMERICAL PREDICTION METHOD FOR HURRICANES

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ABSTRACT

Seventeen forecasts of hurricane tracks, each up to 72 hours, were made by numerical methods under operational conditions as a test of Kasahara's [5] prediction model. Although the small size of the sample precludes making firm conclusions, the results here obtained compare unfavorably with the regularly issued subjective forecasts. In general, the forecast motion is too slow and to the right of the actual hurricane track.

1. INTRODUCTION

The numerical hurricane forecasts described in this report were made to test operationally a prediction model developed by Kasahara [5] at the University of Chicago under a Weather Bureau contract and to test the effect of independent analyses on the forecast. The number of independent analyses available for making duplicate forecasts was, however, unfortunately small.

The fact that this test was made under operational conditions on a "real time" basis enhances its value because there was no possibility that an unconscious bias could be inserted by an analyst who knew the actual hurricane track. Moreover, because the analyses had to be completed by a deadline, they were handicapped by late and missing data in the same manner as the analyses made in hurricane forecast centers, thereby simulating actual operating conditions.

Analyses made by Dr. Riehl at the University of Chicago during his stay at the National Hurricane Research Project, West Palm Beach, Fla., during the 1958 hurricane season were used to produce duplicate forecasts. It so happened that the analysis routine at West Palm Beach produced only three 500-mb. maps for the same time as those made by the writer, so only three comparisons are available. The effect of different analyses is illustrated, but no significant statistics can be derived.

Each hurricane forecast consists of the following steps:

1. Derive graphically the scale and height profile of the hurricane vortex shown on the 500-mb. analysis.
2. Subtract that vortex from the 500-mb. analysis.
3. Produce a stream function field of the 500-mb. surface resulting from step 2 by means of the balance equation routine used by the Joint Numerical Weather Prediction (JNWP) Unit [8].
4. Produce a numerical forecast up to 72 hours on the stream function field from step 3, using the JNWP barotropic-divergent model on the hemispheric octagonal grid [1].
5. Compute a point trajectory starting from the position of the hurricane center on the initial map by use of the hourly forecast fields produced in step 4.

2. METHOD OF ANALYSIS

The 500-mb. analysis used for this test was the machine analysis of the Northern Hemisphere produced by the JNWP automatic data reduction and analysis routine, modified by a reanalysis of the tropical and subtropical Atlantic and Caribbean regions. Figure 1 shows the area that was reanalyzed.

The procedure was to analyze the modification area, perform steps 1 and 2, and substitute the modified analysis (with the vortex removed) into the machine analysis of the octagonal grid, then produce a stream function field (step 3).

Reanalysis was necessary because the region east and northeast of the Antilles is largely devoid of upper-air data and a reliable 500-mb. analysis can be made only by a careful consideration of the surface analysis and the thermal characteristics of tropical atmosphere [4]. While this yields improved analysis within the modification area, it created a problem in making the transition from modi-

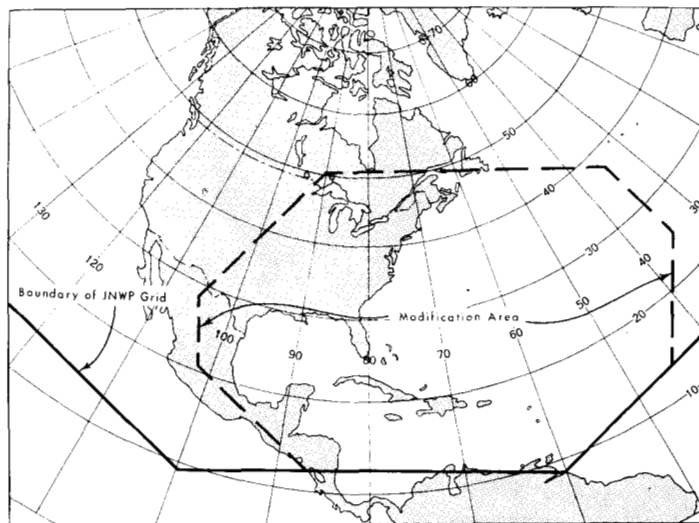


FIGURE 1.—Reanalysis area.

fied to unmodified analysis. At low latitudes especially it was difficult to obtain a smooth transition because the machine analysis frequently produced abnormally low 500-mb. heights on the southern boundaries of the analysis. This was probably due to an error in the analysis routine (corrected shortly after the hurricane season) that extrapolated pressure heights into regions of no data on the basis of erroneous gradients wherever winds were incorporated. Fortunately this error was insignificant at middle latitudes, so the artificial perturbations introduced at the boundaries of the modification area were always in the Tropics and of a small scale; consequently they were quickly smoothed in the forecast routine because waves of less than four grid intervals are not retained.

Hurricane tracks forecast by this method were verified with the official published tracks [9]. Because the official hurricane positions were not available at the time of making the forecasts, several of the initial positions used were different from those that were published, so in order to make a true comparison between forecast and actual motion, the forecast tracks were shifted bodily so that the forecast effectively started from the official initial position. It was necessary to make some adjustment to nine of the forecast tracks; the average adjustment was 34 n.mi.

3. SUMMARY OF FORECAST RESULTS

A total of 17 forecasts was made, each for a 72-hour period. Figures 2-15 show actual and forecast tracks; the errors are tabulated in table 1 and summarized in the polar diagrams, figures 16-20. The polar diagrams show the distribution of forecasts both in a coordinate system pointing in the direction of storm motion and in a system whose orientation remained fixed relative to north. The actual hurricane position at the end of the forecast period is represented by the origin of the diagrams, and the direction of motion is defined as the vector drawn on a polar stereographic map projection from the initial hurricane

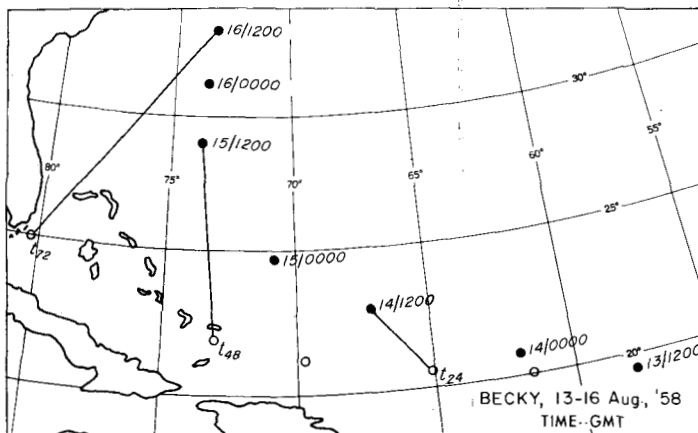


FIGURE 2.—Actual (solid circles) and forecast positions (open circles) for hurricane Becky 1958 for 24 hours (t_{24}), 48 hours (t_{48}), and 72 hours (t_{72}) from position at 1200 GMT, August 13. Lines connect corresponding forecast and actual positions.

TABLE 1.—Errors in forecast hurricane tracks

Storm	Code on figs. 16-19	Date (1200 GMT)	Forecast error (n. mi)		
			24 hr.	48 hr.	72 hr.
A. FORECASTS MADE FOR OPERATIONAL TEST					
(Becky)*	B-1	13 August 1958	(183)	(427)	(620)
Becky	B-2	14 August 1958	232	356	938
(Cleo)	C-1	15 August 1958	(400)	(765)	(992)
(Cleo)	C-2	16 August 1958	(378)	(618)	(1,120)
Cleo	C-3	17 August 1958	117	133	369
Daisy	D-1	25 August 1958	233	393	636
Daisy	D-2	26 August 1958	30	143	418
Daisy	D-3	27 August 1958	109	313	404
Daisy	D-4	28 August 1958	107	209	235
Ella	E-1	1 September 1958	194	364	684
Ella	E-2	2 September 1958	52	212	592
Ella	E-3	4 September 1958	193	399	
Fifi	F-1	7 September 1958	201	381	585
Fifi	F-2	8 September 1958	154	378	778
Average error			147	274	564
B. FORECASTS MADE FROM INDEPENDENT ANALYSIS					
Becky	B-2	14 August 1958	316	524	1,320
Ella	E-1	1 September 1958	157	238	244
Fifi	F-1	7 September 1958	88	233	468

*Forecasts indicated by parentheses not included in average error figure shown here or in "center of gravity," figs. 16-19.

position to the position at the end of the appropriate forecast period.

Each diagram also shows a "center of gravity" of the forecast distribution, but it should be noted that these

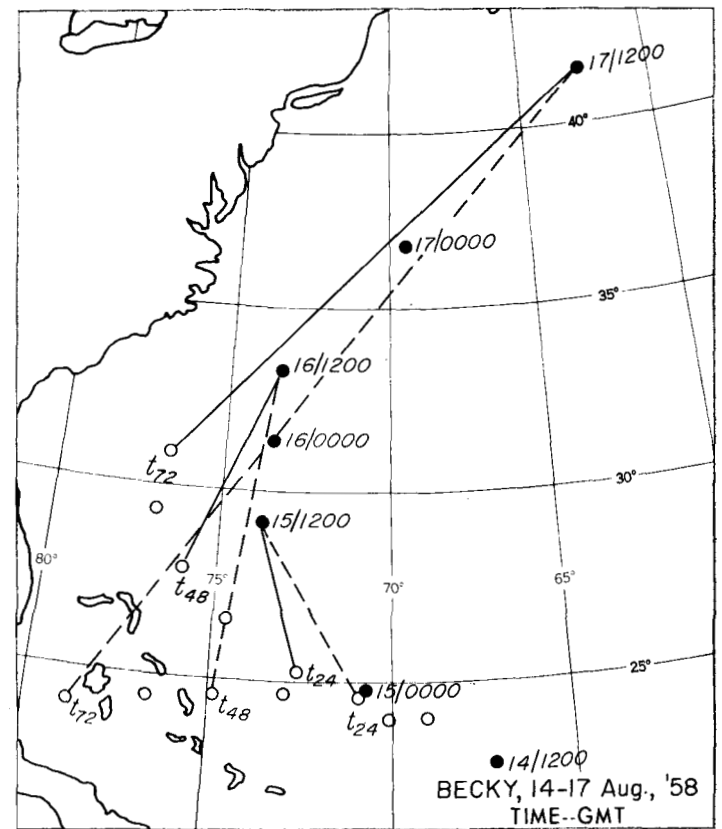


FIGURE 3.—Actual (solid circles) and forecast positions (open circles) for hurricane Becky 1958 from 1200 GMT August 14. Actual position is connected to test forecast position by solid line, to position forecast from independent analysis by dashed line.

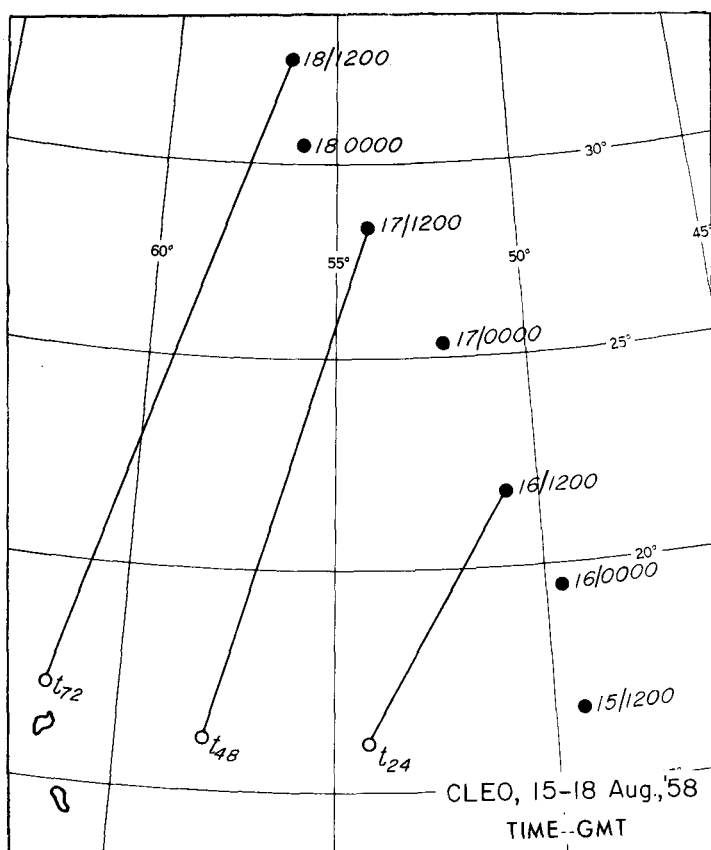


FIGURE 4.—Hurricane positions (solid circles) and forecast positions (open circles).

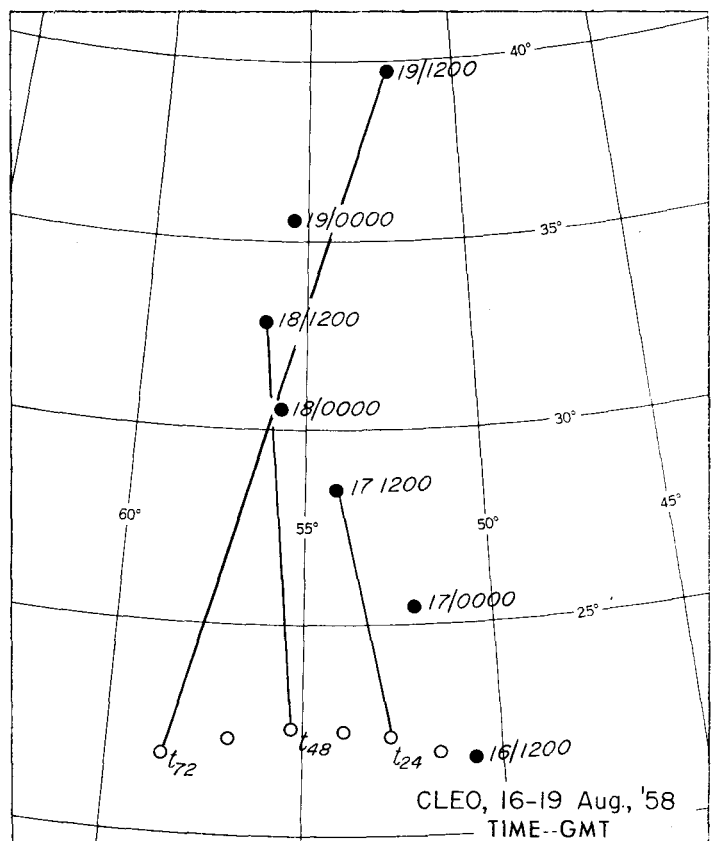


FIGURE 5.—Hurricane positions (solid circles) and forecast positions (open circles).

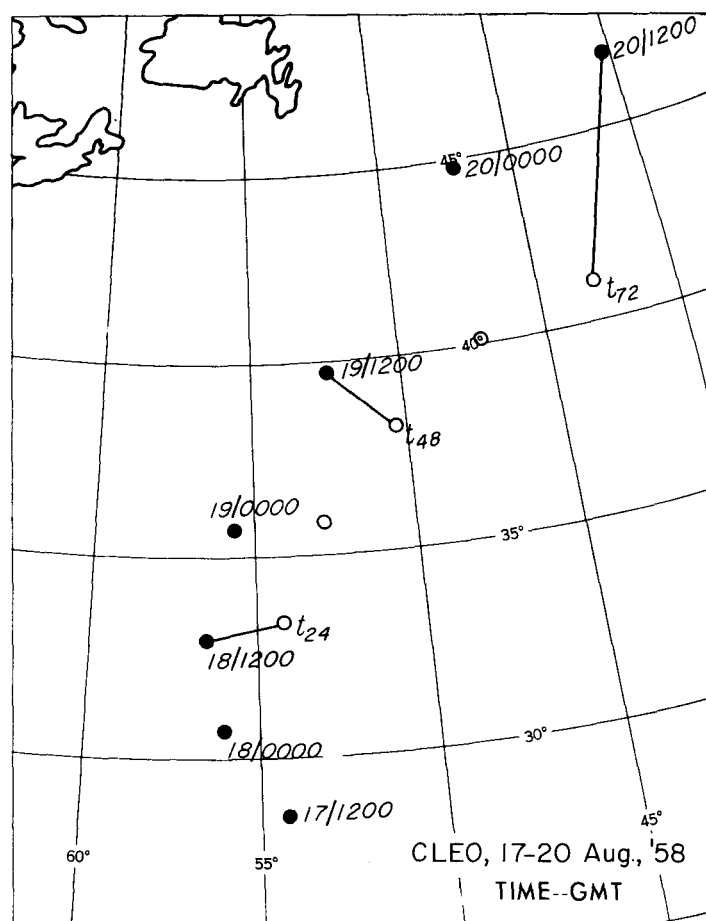


FIGURE 6.—Hurricane positions (solid circles) and forecast positions (open circles).

statistics refer to but 11 of the forecasts. Three forecasts based on Dr. Riehl's analyses were considered as a separate sample. In addition, three "real time" forecasts—Becky, 13 August; Cleo, 15 August; and Cleo, 16 August 1958—were omitted from verification statistics because the area in which they moved during the forecast period was quite near the boundary of the computation grid. As a consequence, the field of motion was not realistically forecast because of the boundary conditions required by mathematical considerations. In addition, that particular area is situated so far from upper-air data that the analyses were open to serious question.

The center of gravity shown on the polar diagrams indicates that forecast motion was too slow and to the right of the actual track. On the north-oriented diagram a bias toward the north and northeast is suggested.

4. DISCUSSION OF FORECAST RESULTS

ERROR ALONG DIRECTION OF MOTION

The tendency to forecast motion too slow is partly due to truncation error, a shortcoming of the numerical procedure of using finite difference quotients as an estimate of derivatives which was discussed in an earlier experiment [3], but in the present model the vortex subtraction

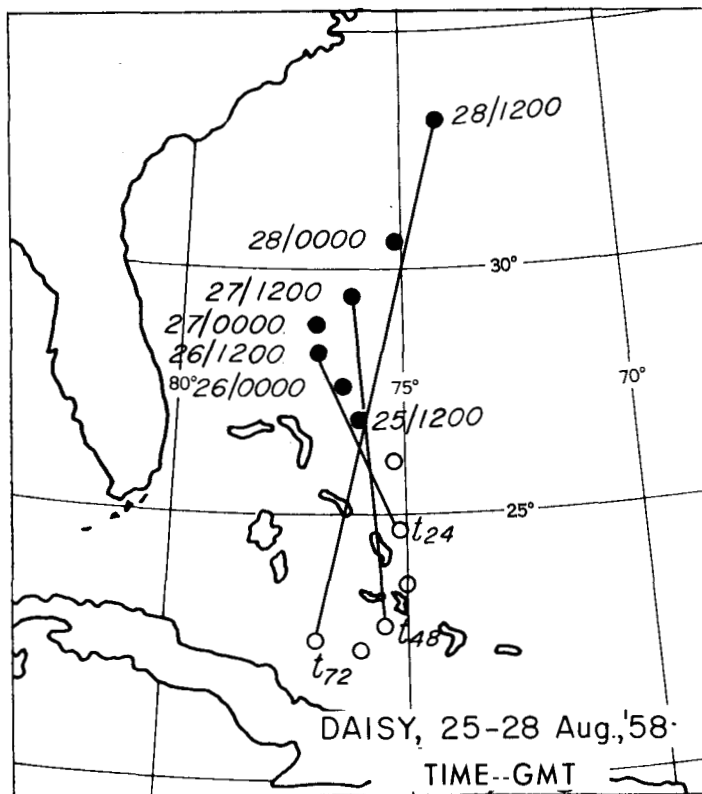


FIGURE 7.—Hurricane positions (solid circles) and forecast positions (open circles).

adds another possible source of speed bias. When the hurricane lies near a col the effect of subtracting the vortex is to produce an extremely flat gradient right at the point where the trajectory starts.

At this stage the method of smoothing the residual flow field is critical. Because the large-scale forecast with the barotropic model does not change details of this nature very rapidly, the initial gradient usually persists for many hours in the forecast field so that the storm displacement is largely dependent upon the initial conditions.

ERROR TO RIGHT OF DIRECTION OF MOTION

The bias toward the right might be due either to a tendency for hurricanes to move to the left of the geostrophic wind at the 500-mb. level or to a systematic error in the numerical forecast procedure that produced the bias toward the right of the geostrophic wind. In this small sample with the great dispersion of forecast errors it is of course impossible to determine the cause for the bias, but certain indications do appear that yield insight into the sources of error.

Concerning the possible tendency for hurricanes to move to the right of the geostrophic wind at the 500-mb. level, there is no indication in other work on the subject that such a tendency exists (e.g., see [6] and [7]). As a consequence, it is reasonable to examine the forecast routine for the probable cause.

To begin with, it should be noticed that the direction of the storm forecast in this test was generally toward

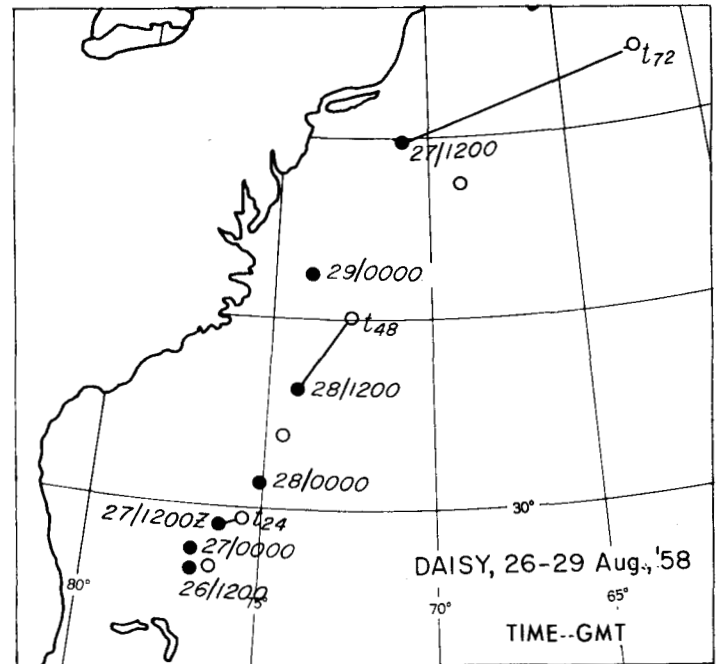


FIGURE 8.—Hurricane positions (solid circles) and forecast positions (open circles).

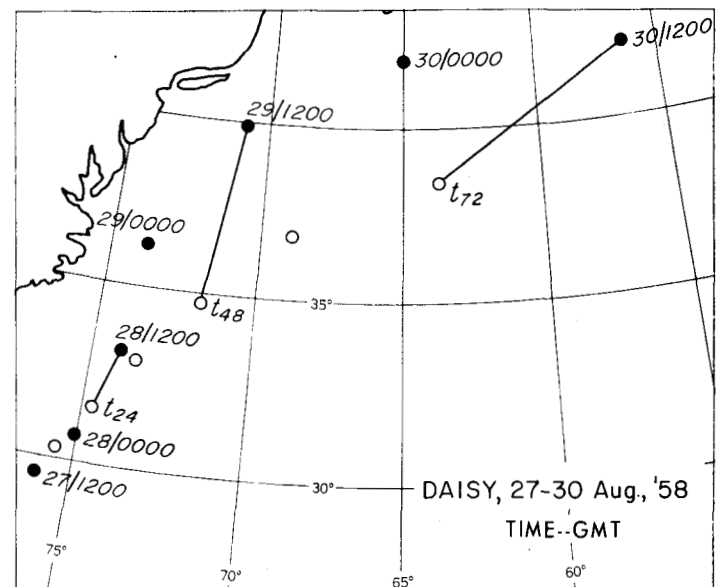


FIGURE 9.—Hurricane positions (solid circles) and forecast positions (open circles).

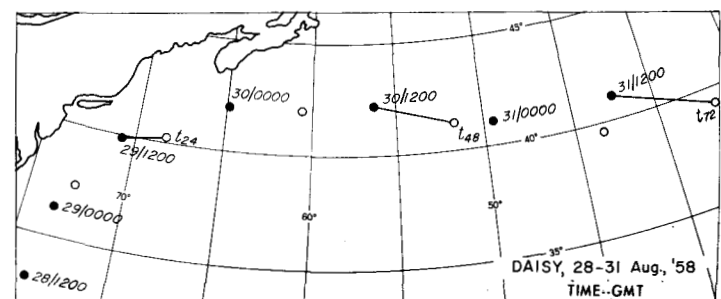


FIGURE 10.—Hurricane positions (solid circles) and forecast positions (open circles).

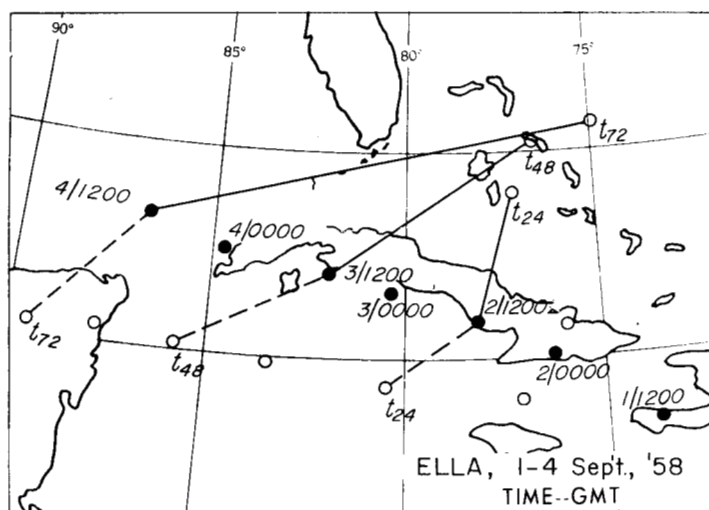


FIGURE 11.—Hurricane positions (solid circles) and forecast positions (open circles). Actual position is connected to test forecast position by solid line, to position forecast from independent analysis by dashed line.

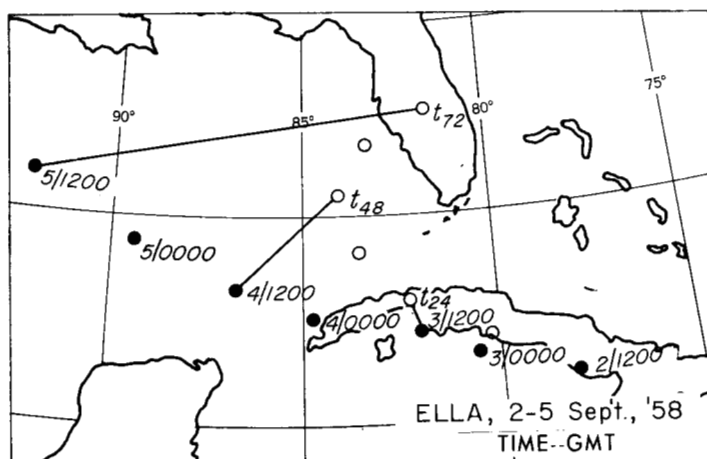


FIGURE 12.—Hurricane positions (solid circles) and forecast positions (open circles).

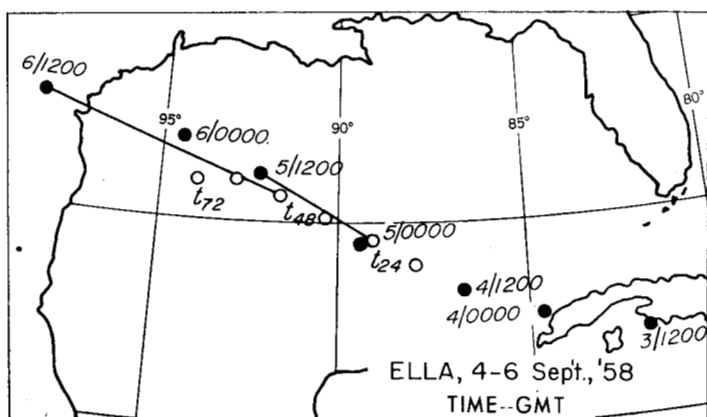


FIGURE 13.—Hurricane positions (solid circles) and forecast positions (open circles).

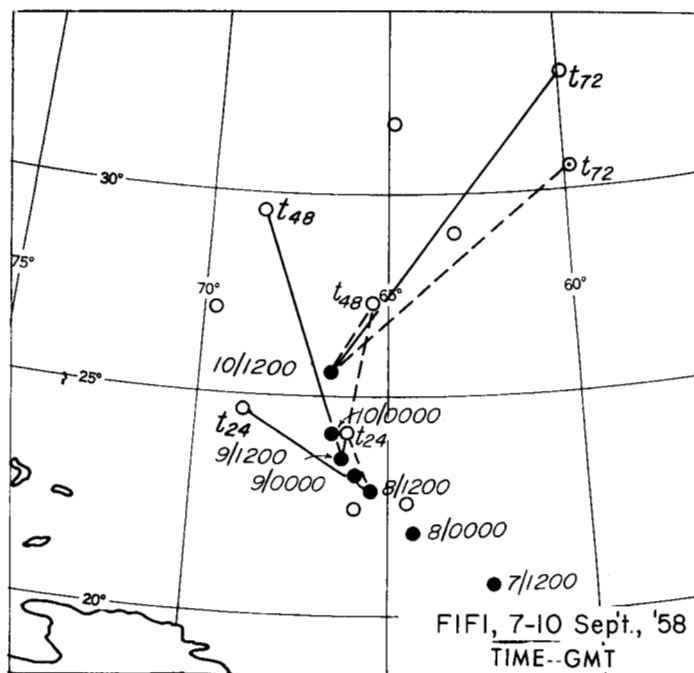


FIGURE 14.—Hurricane positions (solid circles) and forecast positions (open circles). Actual position is connected to test forecast position by solid line, to position forecast from independent analysis by dashed line.

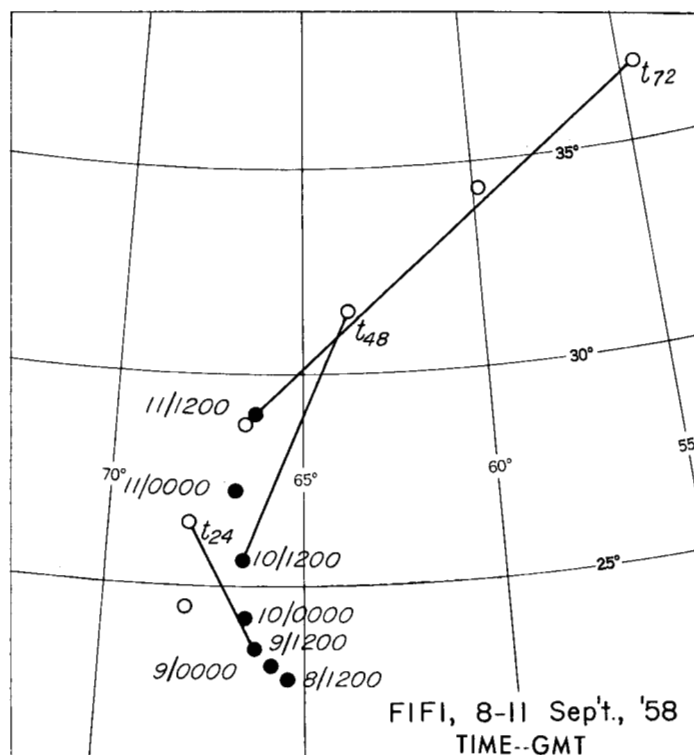


FIGURE 15.—Hurricane positions (solid circles) and forecast positions (open circles).

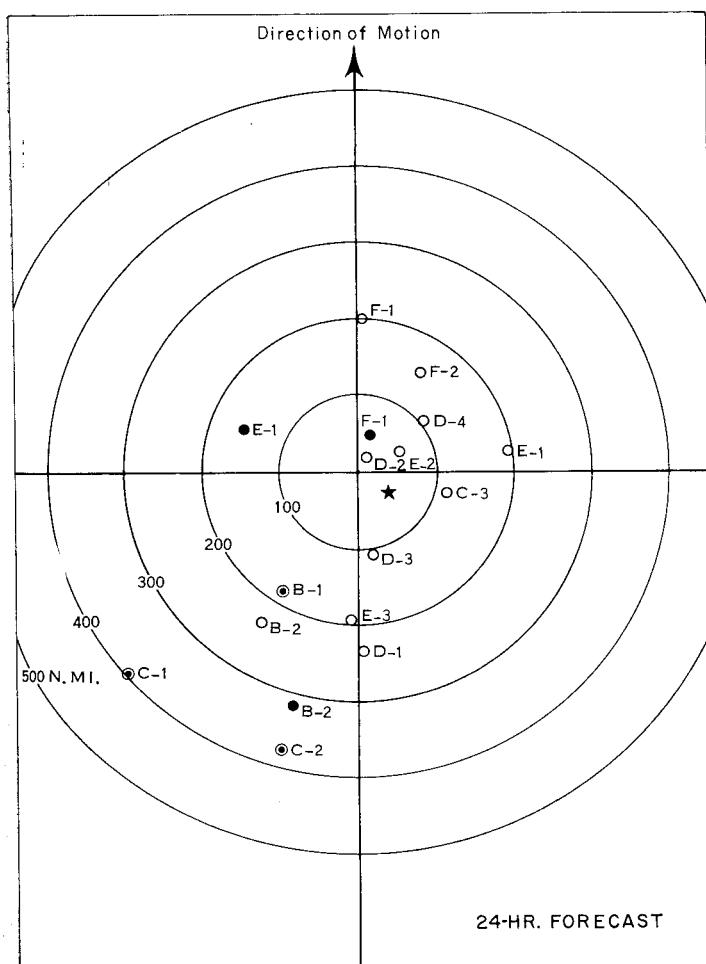


FIGURE 16.—Distribution of 24-hour forecasts relative to direction of motion. Star marks centroid. Storm identifiers listed in table 1.

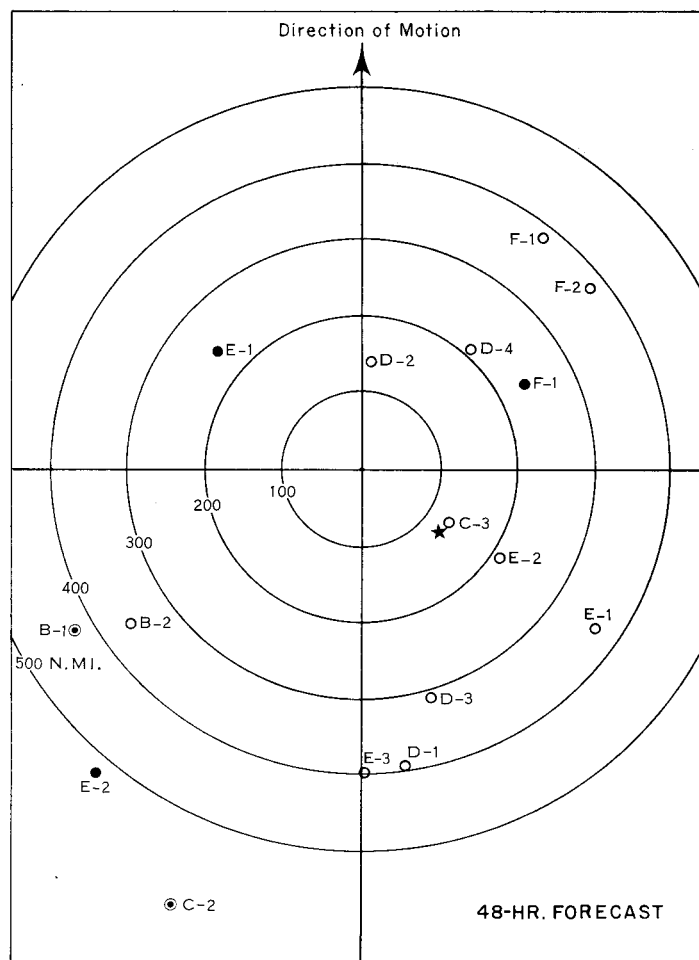


FIGURE 17.—Distribution of 48-hour forecasts relative to direction of motion. Star marks centroid for open circles. Storm identifiers listed in table 1.

the northwest so that a bias to the right of the true track would also show up as a bias toward the east. Now if a systematic error in the trajectory computations produced the bias, it would arise because of the systematic influence of a residual trough left by the vortex subtraction or through the vortex interaction term in the trajectory equations. Examination of the forecast stream function fields showed that the bias was not due to a residual trough; therefore the effects of the trajectory computations were examined.

Trajectories are computed in step 5 of the forecast procedure by application of:

$$C_x = -a \frac{\partial \psi}{\partial y} - K \frac{\partial \eta}{\partial y} \quad (1)$$

$$C_y = a \frac{\partial \psi}{\partial x} - K \frac{\partial \eta}{\partial x} \quad (2)$$

C_x = trajectory speed along the x -axis

C_y = trajectory speed along the y -axis

ψ = stream function

η = absolute vorticity ($f + \zeta = \eta$) where ζ is the relative vorticity and f the Coriolis parameter

a = a constant for scaling to proper units

K = a number obtained from the hurricane profile on the 500-mb. surface to represent the magnitude of the vortex (contains the appropriate scale factor a)

The first terms on the right side of equations (1) and (2) are the geostrophic wind components in the stream function field, while the last terms, depending upon the size of the hurricane vortex (K) and the gradient of absolute vorticity ($\Delta\eta$), are the vortex interaction terms.¹

Now in this particular model a symmetric vortex is removed (step 2) so that the residual relative vorticity is a measure of the asymmetry about the storm. Since there is no gradient of Coriolis force in an east-west direction, it is only asymmetry in the east-west direction that can produce a north-south component of storm motion. On the other hand, the east-west component contributed by this term depends upon the asymmetry along a north-south axis combined with the north-south gradient of Coriolis force. It is therefore of interest to estimate the magnitude of the interaction term in these cases and to determine whether the contribution was in the correct direction.

¹ It will be noticed that this "interaction" term is actually unilateral, for the 500-mb. field influences the hurricane trajectory, but the vortex, having been removed before the forecast starts, can have no effect on the 500-mb. field.

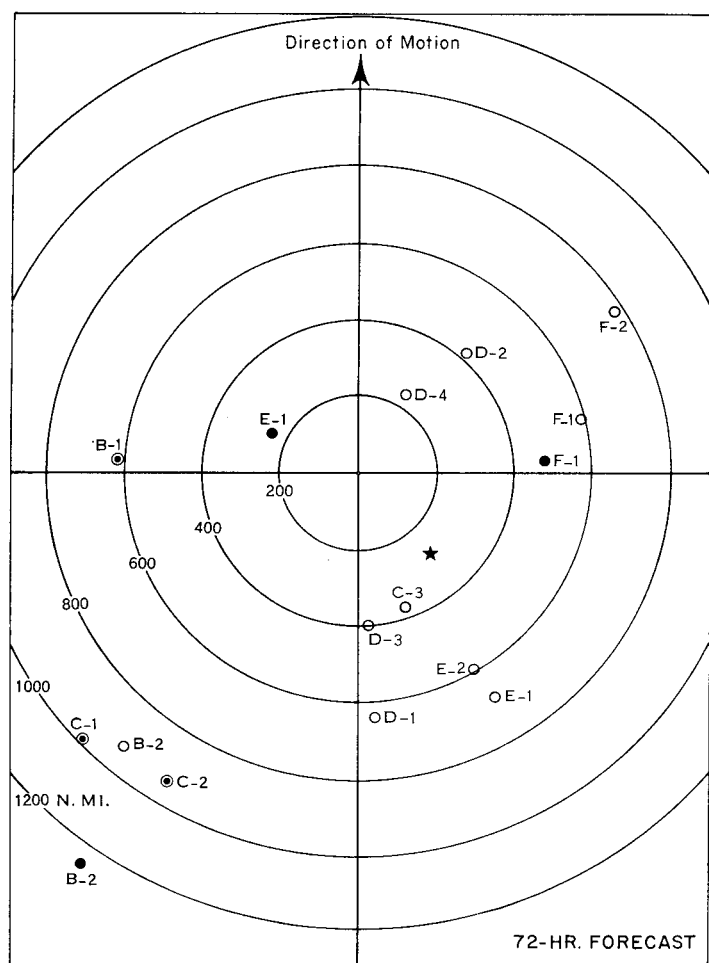


FIGURE 18.—Distribution of 72-hour forecasts relative to direction of motion. Star marks centroid for open circles. Storm identifiers listed in table 1.

On the basis of figures 19 and 20, which show a bias toward the east, indications are that the effect of the Coriolis term in the trajectory equations is in the proper direction, for without it the error would have been even greater toward the east.

In an effort to make some quantitative estimate of the effect, two different trajectory computations were made on four storms; the first trajectory by the procedures outlined above and a second computation following the same routine except that the vortex interaction term was eliminated so that the motion was entirely due to the "balanced" wind. The differences between these trajectories are tabulated in table 2. Where the effect of the vortex term and the forecast error have opposite signs, the effect of the term was to reduce the error; where the signs are the same, the effect was to increase the error. The underlined items are the cases where the effect was favorable.

First, it is clear that the contribution of the Coriolis term to the absolute vorticity gradient is a prominent effect for the signs in the third column are all negative (displacement to the west). Since the signs in the fourth column are a function of the relative vorticity gradient only, there is an indication that the gradient of relative

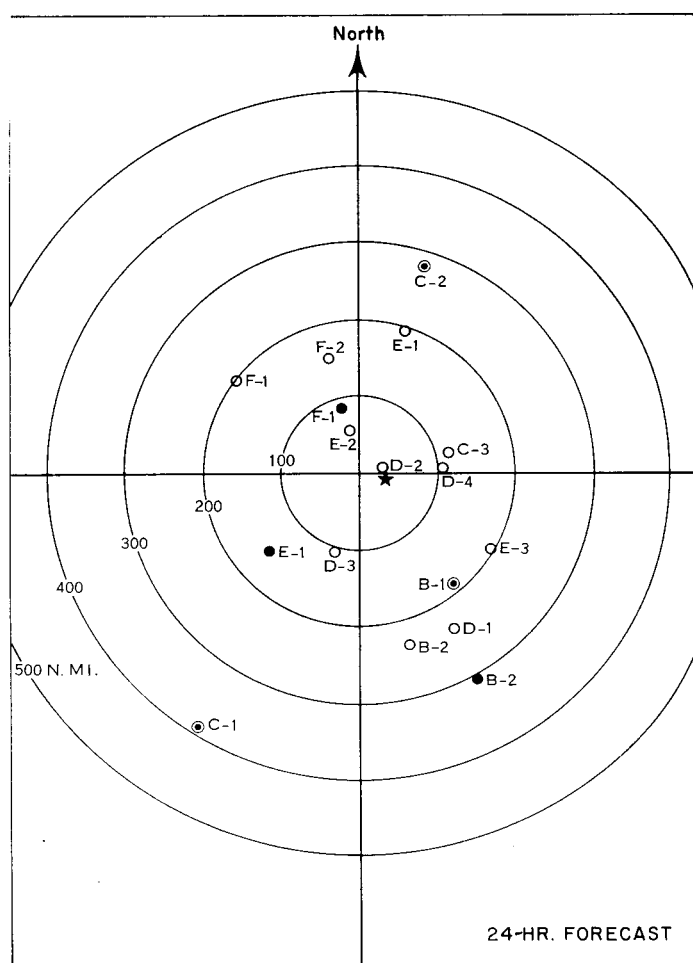


FIGURE 19.—Distribution of 24-hour forecasts relative to north. Star marks centroid for open circles. Storm identifiers listed in table 1.

vorticity in an east-west direction is generally smaller than the gradient of Coriolis force in the north-south direction—an indication of the small asymmetry in the cases tested.

Second, the overall influence of this term has been beneficial for there are more favorable cases than unfavorable.

Third, the most definitive result is the indication that the influence of the vortex term in this model is insignificantly small for storms of the size tested for it contributes displacement in 24 hours that is less than the uncertainty in hurricane position.

TABLE 2.—Forecast error compared to effect of vortex interaction term (in units of grid lengths, 381 km. at 60°)

Storm and forecast	Vortex scale, K (km.)	Effect of vortex interaction term—		24-hour forecast error—	
		To east	To north	To east	To north
Daisy-1.....	200	—0.05	—0.03	0.05	0.20
Ella-3.....	210	—0.07	0.02	0.40	—0.40
Fifi-1.....	150	—0.03	0.00	—1.30	1.00
Fifi-2.....	125	—0.02	—0.02	—0.05	0.75

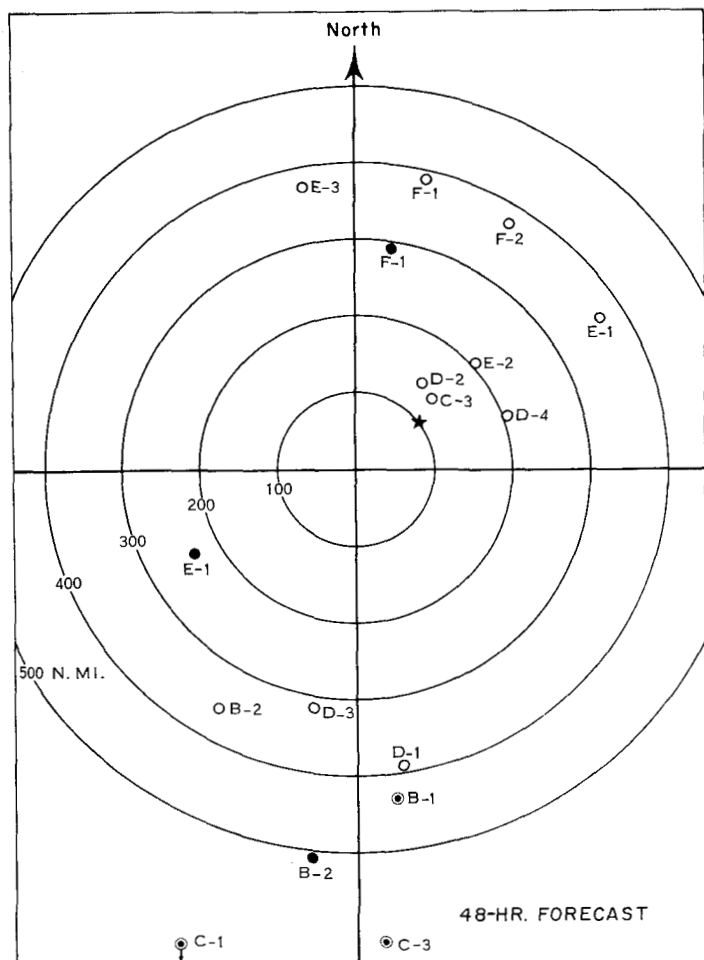


FIGURE 20.—Distribution of 48-hour forecasts relative to north. Star marks centroid for open circles. Storm identifiers listed in table 1.

5. ERROR IN FORECASTING LARGE-SCALE FEATURES

The error in hurricane trajectory forecasts that was contributed by inaccuracies of the numerical weather prediction model in predicting large-scale features was investigated by computing trajectories on observed rather than on forecast stream function fields. This was possible of course only where forecast steps 1, 2, and 3 had been completed on successive days, a requirement which limited the sample to five cases of 24-hour forecasts. Figure 21 illustrates the results that would have been realized if the large-scale pattern had been "perfectly" forecast; that is, if the forecast valid 24 hours after the initial time had been exactly the same as the stream function map obtained from analysis of the actual data 24 hours after the initial map. This polar diagram shows both the forecast positions and the positions computed from a "perfect forecast," as well as the centers of gravity. The average error for those five forecasts was 118 n. mi. in 24 hours; the "perfect large-scale forecast" would have given an average error of 74 n. mi.—an improvement of 44 n. mi.²

²The error of 74 n. mi. that occurs despite a "perfect large-scale forecast" is in part a reflection of the fact that the analysis of actual data includes a certain degree of uncertainty and thus does not actually represent a perfect forecast.

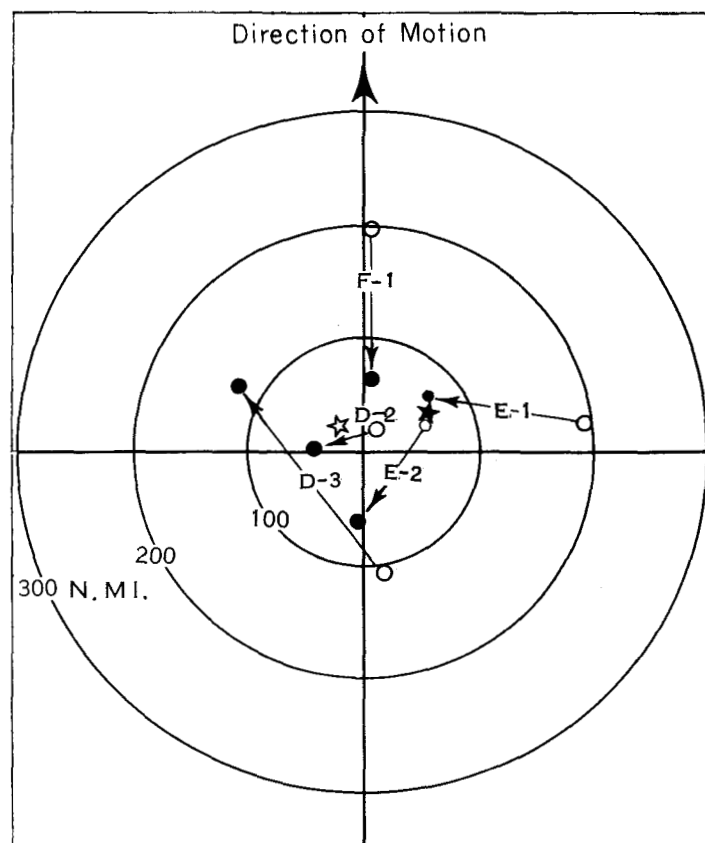


FIGURE 21.—Distribution of 24-hour forecasts (open circles) and 24-hour motion computed from observed stream function fields (solid circles) for the same period. Respective centroids indicated by stars.

Another source of error that is peculiar to this method concerns the solution of the balance equation in regions of a flat gradient such as sometimes results from subtracting the hurricane vortex. This is illustrated by the Daisy forecast of 25 August (fig. 7). Minor features in the flat height field produced a small anticyclone in the stream function field which in turn produced a forecast trajectory that spiraled to the south while the hurricane actually drifted northward. It is not obvious from inspection of the 500-mb. height field just what the balance equation solution will produce insofar as these minor features are concerned, and it sometimes turns out that features quite unimportant to the large-scale forecast produce a minor eddy which can then dominate the point trajectory.

In summary, it appears that a significant part of the error is due to shortcomings of the numerical model in predicting the large-scale pattern, but that *uncertainty in the analysis due to sparse data is an equally serious source of error* quite apart from the method of hurricane track forecasting applied.

6. CONCLUSIONS

A comparison of the results reported here with various verification statistics on subjective hurricane forecasts reveals that numerical hurricane forecasts by this model

in its present state of development are not competitive with subjective forecasts issued by hurricane forecast centers, either short range or for 3 days. There is a question, however, if this is the manner in which to use numerical forecasts of this type. Perhaps they should be used as a frame of reference to be modified by subjective methods where possible. Such an approach would preclude using this type of machine forecast when some accidental event in the routine produced a trajectory that was clearly unreasonable. For example, the Daisy forecast just discussed would cause the forecaster to reexamine the situation to see if it appeared reasonable for a closed anticyclone to develop in the critical area. Examination of the initial stream function field would have revealed in this case that it was a product of balance equation solution of the initial field and not a forecast at all, so the southerly trajectory forecast would have been discarded.

A numerical forecast that would be operationally more useful could of course incorporate the knowledge used by the subjective forecasters. For example, the past motion as well as climatology could easily be included in the machine forecast to yield a combined dynamic-kinematic forecast that would take advantage of empirical knowledge that serves the human forecaster. The first steps in this direction already have been taken by the JNWP Unit. A method developed incorporates past motion into the analysis, and the hurricane forecasts for the 1959 season are expected to show the resulting improvement.

Conclusions based on such a small sample are not justified, but the various indications resulting from this analysis point to aspects of this scheme that should receive additional study.

Because the balance equation can produce minor features that do not harm the large-scale forecast but that can be disastrous to a point trajectory, some space smoothing of the stream function field is mandatory before tra-

jectories are computed. A surface-fitting technique such as that reported in [2] may well serve this function.

The subtraction of a symmetric vortex does not always leave a smooth basic flow field because of initial irregularities in the analysis—some of which are due to inaccurate or inadequate data. It is therefore indicated that the method of vortex subtraction might be revised.

Finally it is clear that an accurate hurricane forecast depends upon an accurate forecast of the large-scale pattern, and the current status of our upper-air observations in oceanic regions limits the ability of any model to eliminate this source of error in the near future.

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9. Staff, Weather Bureau Office, Miami, Fla., "The Hurricane Season of 1958," *Monthly Weather Review*, vol. 86, No. 12, Dec. 1958, pp. 477-485.

CORRECTION

Vol. 87, April 1959, p. 133: In figure 4, $\Delta T/\Delta t$ should be -0.8° C. at 425 mb. and -1.2° C. at 475 mb.

P. 134: In figure 5, $\Delta T/\Delta t$ should be -0.8° C. at 475 mb. and -1.4° C. at 625 mb.